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Review

Cardiopulmonary resuscitation for cardiac arrest: the importance of uninterrupted chest compressions in cardiac arrest resuscitation

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Abstract Over the last decade, the importance of delivering high-quality cardiopulmonary resuscitation (CPR) for cardiac arrest patients has become increasingly emphasized. Many experts are in agreement concerning the appropriate compression rate, depth, and amount of chest recoil necessary for high-quality CPR. In addition to these factors, there is a growing body of evidence supporting continuous or uninterrupted chest compressions as an equally important aspect of high-quality CPR. An innovative resuscitation protocol, called *cardiocerebral resuscitation*, emphasizes uninterrupted chest compressions and has been associated with superior rates of survival when compared with traditional CPR with standard advanced life support. Interruptions in chest compressions during CPR can negatively impact outcome in cardiac arrest; these interruptions occur for a range of reasons, including pulse determinations, cardiac rhythm analysis, electrical defibrillation, airway management, and vascular access. In addition to comparing cardiocerebral resuscitation to CPR, this review article also discusses possibilities to reduce interruptions in chest compressions without sacrificing the benefit of these interventions.

1. Introduction

Over the past several decades, cardiopulmonary resuscitation (CPR) has undergone significant change with, of course, the focus being the improvement in patient outcomes. All aspects of CPR have become a focus of research and scrutiny. For instance, from 1981 to 1983, 2 investigations using animal models were designed to find ideal compression depth and rate that would maximize cardiac output during arrest; these studies suggested the depth and rates that remain in use today [1,2]. Another study from 1988 showed that after a ventricular fibrillation (VF) arrest, the 24-hour survival in a canine model was superior with a compression rate of 120 per minute compared with a rate of 60 per of minute [3]. These studies and others [4,5] with clinically relevant end points published in the decades since show that deep compressions with full chest recoil performed at an appropriate rate are important aspects of effective CPR—with direct impact on survival and neurologic outcome.

The conclusion that compressions should be “hard and fast” is generally well accepted and is reflected in the American Heart Association’s (AHA) newest CPR guidelines released in 2010, which emphasize the importance of delivering high-quality compressions while minimizing interruption [6]. There is little debate that high-quality

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compressions have a positive effect on arrest outcomes, but the AHA's newest guidelines also refer to evidence suggesting that decreasing interruptions in compressions likely are just as important as compression rate or depth. Over the past 15 years, there has been a growing body of evidence showing that patients who receive CPR in the field earlier are more likely to survive [7,8]. This new knowledge, however, has been offset by other studies showing that laypersons and health care providers alike are becoming less likely to perform CPR, possibly because of an increased awareness of communicable diseases and fear of disease transmission during mouth-to-mouth breathing [9,10].

Despite advances in technology and emergency medical services (EMS) training over the past decade, outcomes from out-of-hospital cardiac arrest remain unchanged with relatively low rate of neurologically intact survival. Recognition of these problems coupled with an increased understanding of the physiology of cardiac arrest has led investigators to explore forms of CPR that minimize compression interruptions with very promising results [11]. These investigators, before the release of the most recent AHA Guidelines 2010, have suggested that adequate chest compressions when performed with minimal interruptions will provide the cardiac arrest patient with the best opportunity for functional survival.

2. Cardiocerebral resuscitation—minimally interrupted CPR

The University of Arizona Sarver Heart Center Resuscitation Group is one of the groups leading this effort in resuscitation. In 2003, they departed from the AHA's guidelines and instituted their own resuscitation protocol, known as cardiocerebral resuscitation (CCR) in Tucson, Arizona [12]. Since this early introduction, CCR has been used in numerous fire rescue services in Arizona as well other as in other areas such as rural Wisconsin. Interestingly, at each site where CCR is used, the rate of neurologically intact survival after witnessed out-of-hospital arrest has dramatically improved [12-15]. Compared with standard CPR with traditional AHA advanced cardiac life support management approach, CCR places much more emphasis on minimizing interruption of chest compressions, delivering sets of 200 compressions while stopping only for rhythm analysis and single defibrillatory shocks if warranted by the cardiac rhythm. "Passive oxygenation" via nonrebreather mask with oral airway in place—that is, the absence of bag-valve-mask (BVM) ventilation—is the primary airway management in the early phase of resuscitation of CCR; positive pressure ventilation is not attempted until 8 to 10 minutes into the resuscitation per the CCR protocol [14].

Not surprisingly, the absence of rescue breathing in this protocol is a source of hesitation for some clinicians, but the developers of this technique argue that, in cardiac arrest, the benefits of uninterrupted chest compressions outweigh the benefits of rescue breathing—at this early stage of resuscitation—because the physiology of cardiac arrest differs from that of asphyxial arrest, where breathing is initially more important [16]. Cardiocerebral resuscitation is a bold step forward that is supported by animal model studies showing neurologically intact survival benefits associated with continuous compressions conducted at the University of Arizona [17,18] that have also been corroborated by other groups [19,20]. Furthermore, this technique was associated with neurologically intact survival benefits in humans when used by rescuers [14,21].

In addition to using animal models and survival outcomes as a foundation, CCR also incorporates recent advances in cardiac arrest physiology. The CCR protocol addresses a 3-phase model of ventricular fibrillation physiology described by Weisfeldt and Becker [22]. In this model, the first 5 minutes of arrest is called the "electrical phase," during which time electrical defibrillation can result in the return of spontaneous perfusion. After approximately 5 minutes of fibrillation, the heart's energy stores become exhausted, and even if an electrical shock is delivered, the return of spontaneous circulation (ROSC) is less likely. This phase, which lasts for approximately 5 to 10 minutes, is known as the "hemodynamic phase." Finally, after 10 to 15 minutes of sustained cardiac arrest, the heart enters the "metabolic phase," during which time no intervention has yet been shown to have a significant impact on survival.

Sanders et al [23-26] have demonstrated that a major factor affecting survival during the hemodynamic phase of arrest is the maintenance of adequate arterial pressure. During the hemodynamic phase, adequate perfusion of the coronary arteries is necessary to oxygenate the myocardium as well as to clear metabolic waste products, thereby increasing the likelihood that ROSC will be achieved [27]. In addition, adequate perfusion pressure to the brain helps to increase the chances of neurologically intact survival. Interestingly, Berg et al [28] found that coronary perfusion pressure builds gradually during the first few compressions and substantially falls if compressions are interrupted, further supporting the idea that continued compressions provide superior perfusion pressure when compared with interrupted shorter sets of compressions (Fig. 1). Because CCR "targets" the hemodynamic phase of arrest, it is not surprising that survival among patients with witnessed arrests and shockable rhythms is much improved over traditional CPR with standard advanced cardiac life support [12].

Fig. 1 demonstrates the perfusion dependence on active chest compressions. In Fig. 1A, chest compression initiates with a gradual increase in perfusion pressure. Once several consecutive, uninterrupted chest compressions have occurred, perfusion or forward flow in the vascular space occurs. With continued, uninterrupted chest compressions, perfusion pressure ultimately reaches a life-sustaining level, as noted by Berg et al [28]. With discontinuation of chest compressions, all perfusions halt. With resumption of

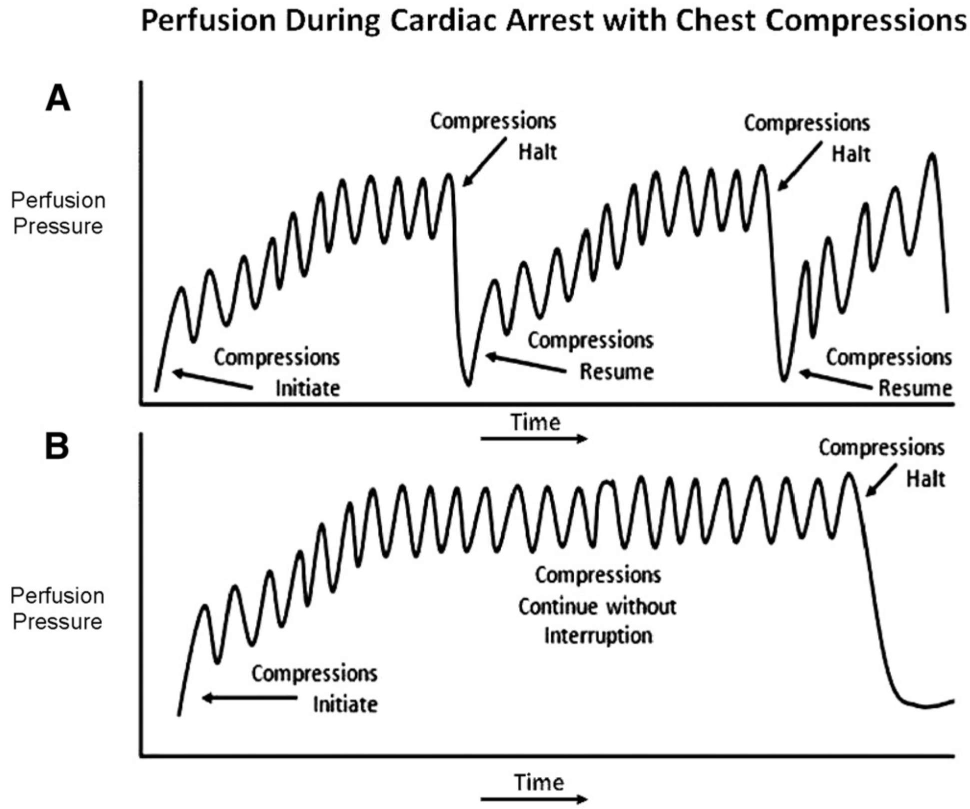

Fig. 1 A, The complete perfusion dependence on active chest compressions in cardiac arrest patient undergoing CPR. Chest compressions initiate with a gradual increase in perfusion pressure. Once several consecutive, uninterrupted chest compressions have occurred, perfusion or forward flow in the vascular space occurs. With continued, uninterrupted chest compressions, perfusion pressure ultimately reaches a life-sustaining level. With discontinuation of chest compressions, all perfusion halts. With resumption of compressions, perfusion pressure once again gradually increases to the previously attained, life-sustaining level over a period. B, Continuous chest compressions are observed with a simultaneous, continuous adequate level of perfusion.

compressions, perfusion pressure once again gradually increases to the previously attained, life-sustaining level. In Fig. 1B, continuous chest compressions are observed with a simultaneous, continuous adequate level of perfusion. It is important to note that with each discontinuation and eventual reinitiation of compressions, life-sustaining perfusion does

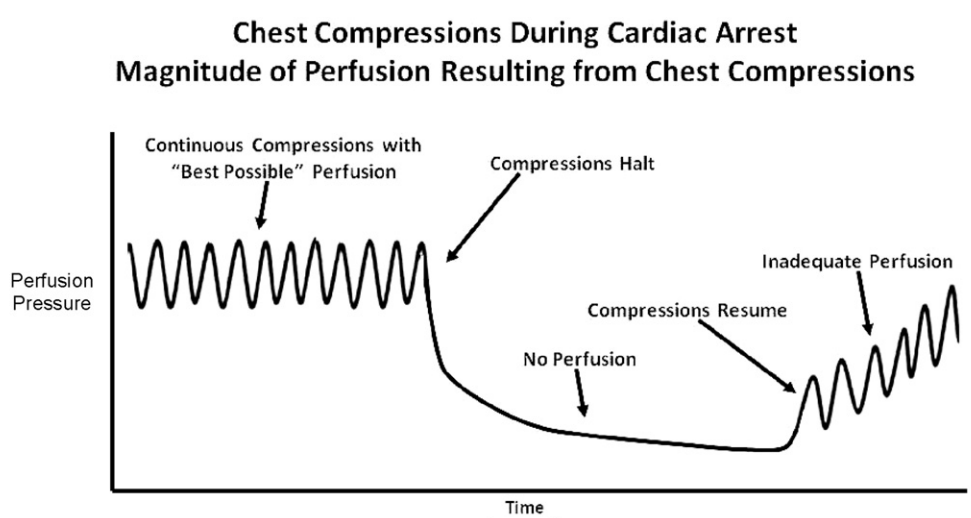

Fig. 2 With prolonged interruptions in chest compression, perfusion is nonexistent for even longer periods, not only including the hands-off period but also during the early resumption of chest compressions.

not immediately occur (Fig. 2). Rather, approximately 40 to 45 seconds elapse during continuous chest compressions before the development of the "best possible" level of perfusion. Thus, the period of nonperfusion includes not only the "hands-off" period of noncompressions but also the initial 45 seconds of chest compression reinitiation (Fig. 2). With prolonged interruptions in chest compression, perfusion is nonexistent for even longer periods, as noted in Fig. 2.

A recent study noted that "more continuous" chest compressions—that is, not only fewer interruptions but also fewer interruptions of shorter duration in performing chest compressions—are associated with improved survival rates in out-of-hospital cardiac arrest with shockable rhythms. These investigators introduced the concept of chest compression fraction (CCF) in their analysis; the *CCF* is defined as the proportion of time during resuscitation that is used in providing chest compressions. This study suggested that increasing CCF is associated with greater rates of ROSC [29].

Cardiocerebral resuscitation has been in practice in Arizona for nearly a decade now, and although it has not been incorporated as the national standard, it has helped to bring continuous compression CPR into the spotlight. Two separate randomized prospective studies were published recently that showed no difference in outcomes between compression-only CPR and traditional CPR [30,31]. Both study groups suggest that because the outcome from compression-only CPR is no worse than traditional CPR, it should be considered as the standard for laypersons because it is easier to teach and retain…and perform. Although the conclusions drawn from these recent studies are more conservative than those put into practice by the Sarver Heart Center Resuscitation Group, a growing body of evidence including both physiologic modeling and survival outcome analyses strongly supports minimally interrupted chest compressions in CPR as at least an equivalent, if not superior, method of resuscitation for cardiac arrest. The key component of this resuscitative approach is the performance of high-quality, uninterrupted chest compressions at an appropriately rapid rate, as suggested by many different investigators from many different resuscitation perspectives.

2.1. Interruption in chest compressions

In the past decade, minimally interrupted chest compression CPR has been incorporated into resuscitation protocols initially with the introduction of CCR in 2003. Furthermore, the 2005 revision of the AHA's guidelines suggested a 30:2 compression-to-ventilation ratio for single rescuers, thus decreasing interruptions in chest compressions [6]. These important steps forward confirm a growing recognition of the importance of maximizing perfusion pressure during cardiac arrest. Berg et al [28] found that during CPR, even brief interruptions in compressions cause a drop in perfusion pressure, which is associated with worsened outcomes. Similarly, Paradis et al [27] found that ROSC is associated with higher initial and maximal coronary perfusion pressure during CPR in humans. Christenson et al [32] found that patients who receive longer periods of continuous compressions during CPR are more likely to survive. With our current CPR guidelines, however, the benefit of continuous compressions is attenuated by other assessment and interventions during resuscitation such as rhythm analysis, delivery of shocks, airway management, vascular access, and cardioactive medication administration (Table 1).

2.2. Pulse determinations

Pulse determinations or "pulse checks" are a primary method used for determining ROSC during CPR. Determining whether a pulse is present during an arrest situation, however, can be difficult even for experienced providers, potentially resulting in excessive pauses of chest compressions. The 2010 AHA guidelines minimize the importance of these "pulse checks" during CPR in an effort to reduce compression interruptions, recommending that no more than 10 seconds should be spent searching for a pulse [6]. In addition, White et al [33] found that there is a low risk of significant injury while performing CPR on patients who are not in cardiac arrest, suggesting that chest compressions will still be effective and beneficial even as pulse checks are reduced. If the clinician is in doubt with respect to the presence of ROSC, chest compressions should be continued; conversely, if ROSC has occurred, chest compressions should be discontinued [34]. There may be a new option to accomplish this without the need for pulse checks and unnecessary pauses in CPR.

In certain situations, end-tidal carbon dioxide (ET-CO_2) monitoring may be useful for determining ROSC. Pokorna et al [35] found that a sudden increase of 10 mm Hg of ET-CO_2 is associated with ROSC in out-of-hospital cardiac arrest patients. Using ET-CO_2 monitoring as described by Pokorna et al, a clinician would be able to forego pulse checks during CPR until a sudden increase in ET-CO_2 is observed, at which time ROSC can be verified. In addition, ET-CO_2 monitoring during CPR may provide information not previously available that could change patient management, such as the ability to predict if ROSC will be achieved [36,37]. Using ET-CO_2 monitoring in this way could be a reasonable alternative to "pulse checks" for many in-hospital cardiac arrests as well as certain out-of-hospital arrests where intubation is otherwise indicated. The placement of an endotracheal tube (ETT) and subsequent ventilation is required for the use of ET-CO_2 monitoring in cardiac arrest patients; of course, the placement of the ETT is not always feasible in the early phase of cardiac arrest management—this limitation in ET-CO_2 monitoring must be considered.

2.3. Cardiac rhythm interpretation

Another significant source of chest compression interruptions during CPR is the hands-off period required for

Table 1 Reasons and potential solutions to chest compression interruption in cardiac arrest resuscitation

Interruption cause	Time impact [a]	Potential solution
Pulse determinations	Small	Observe for signs of life
		Use of ET-CO_2 monitoring for detection of ROSC
Cardiac rhythm analysis	Small	Rapid determination of rhythm with compression discontinuation
		Use of artifact-reduction ECG analysis
Electrical defibrillation	Small-intermediate	Charge defibrillator before discontinuation of chest compressions
		"Hands-on" approach with ongoing chest compressions while defibrillation occurs
Airway management	Intermediate-large	"Passive" airway management early [b] in cardiac arrest
		Defer endotracheal intubation [c] to a later phase of management
		Place ETT during active chest compressions
		Avoid excessive ventilation rates and tidal volumes
Parenteral access	Small-large	Defer vascular access [d] to a later phase of management
		Place vascular access during active chest compressions
		Use of IO device [d]
		Defer placement of central venous access to later phase of management [d]

[a] *Time impact* is defined as such: small, 15 seconds or less; intermediate, 16 to 30 seconds; and large, 31 seconds or more.
[b] *Early in cardiac arrest* is defined as occurring within the initial 5 minutes of cardiac arrest management.
[c] Airway management, including placement of an ETT, should be considered at an earlier phase of management if a primary respiratory issue is considered as a cause of cardiac arrest.
[d] Vascular access should be considered at an earlier phase of management if a primary vascular, hypovolemic issue, toxicologic, or metabolic etiology is considered as a cause of cardiac arrest.

monitor-defibrillator devices to analyze the patient's cardiac rhythm. Although contemporary monitor-defibrillators are very effective in determining if a shock is warranted, they require a significant pause in CPR to perform a rhythm analysis. Snyder and Morgan [38] found that 5 of 6 commonly used defibrillators require more than 12 seconds of hands-off time before a shock is delivered. This pause in chest compressions has been shown to have a significant negative impact on the restoration of ROSC as well as long-term survival [39-41]. Similarly, a reduction in compression interruptions surrounding defibrillation appears to increase the effectiveness of CPR. Sell et al [42] found that a preshock pause of less than 3 seconds is associated with a 6-fold increase in likelihood of ROSC, which when combined with a postshock pause of less than 6 seconds improved to a 13-fold increase in ROSC. The recent change in CPR guidelines to discontinue stacked shocks [6] appears to attenuate the problem of compression pauses for rhythm analysis [43], but new technology is being developed that could essentially eliminate the need to stop compressions during rhythm analysis, further increasing the efficacy of CPR.

In 2007, Berger et al [44] described an adaptive noise-canceling system that effectively subtracts the signal produced by chest compressions from the electrocardiographic (ECG) signal in real time, enabling a monitor-defibrillator device to analyze an ECG rhythm as compressions are being administered. Using a swine model, this system correctly identified ventricular fibrillation in 310 (97%) of 318 cases while compressions were being given, compared with 35 (16%) of 222 cases being correctly identified without the use of noise-canceling software. More recently, an artifact-reduction algorithm was described by Amann et al [49] that requires only the ECG tracing (other algorithms often incorporate additional data such as blood pressure and CPR compression forces [44-48]), which can be implemented on commercially available computer processors. Although this technology is not yet ready to be incorporated into practice, it is rapidly evolving and has potential to improve the practice of CPR in the near future.

2.4. Electrical defibrillation

The 2005 AHA CPR guidelines recommended that compressions be stopped for rhythm analysis, then resumed while the defibrillator charges to reduce the length of preshock CPR pauses [50], introducing yet another interruption in chest compressions. In a study of 3 hospital centers, Edelson et al [51] found that not only was this practice underused, but another method for defibrillator charging was even more effective in reducing preshock pauses than the AHA's recommendation. In this alternative method, the defibrillator is charged near the end of a compression cycle, allowing for analysis and an immediate shock if warranted. In the 30 seconds preceding shock delivery, this anticipatory charging method required only a 3.9-second pause in compressions on average, compared with 11.5 seconds for the AHA's method and 14.8 seconds when compressions were stopped for both analysis and charging [51]. This study does not address patient outcomes, but others have shown that shorter preshock pauses are indeed associated with positive patient outcomes [42,41]. It is important to note that Edelson et al [41] demonstrated that 10 seconds of hands-off time before defibrillation reduces the rate of ROSC in a very significant sense, approaching a 50% decrease in restoration of a perfusing rhythm postdefibrillation.

An interesting criticism of continued compressions during defibrillator charging is that rescuers felt that they were less safe in comparison with the more familiar “hands-free” charging method [52]. Recent studies show that the perceived danger to health care providers concerning defibrillator use is largely based on undocumented cases and may be exaggerated.

A recent study by Lloyd et al [53] challenges the belief that maintaining contact with a patient during defibrillator discharge is potentially very dangerous. In this experiment, 43 biphasic shocks were delivered to patients via self-adhesive defibrillator pads while a gloved rescuer was pressing down on the patient’s chest—simulating the type of contact experienced during chest compressions. In addition, a wire was connected between the patient’s shoulder and the rescuer’s thigh to simulate inadvertent skin-to-skin contact, allowing for completion of a second electrical circuit through the rescuer’s body. Of the 43 shocks, none were perceptible to the rescuers, and only 36 were substantial enough to be detected for analysis [53]. The remaining 36 shocks delivered current well below a common standard for nonhandheld household and business equipment [53]. These results are further supported by a 2009 review of medical literature that found no evidence of serious harm being done to a rescuer or bystander as a result of patient defibrillation [54]. There are published reports of defibrillators causing minor burns and shocks, but most of these come from older literature and involve defibrillator paddles rather than self-adhesive pads [55], suggesting that newer defibrillator equipment may be safe enough to allow for compressions during shock administration, although further study is necessary to ensure the safety of this practice.

2.5. Airway management

Endotracheal intubation is a major source of compression interruptions in both prehospital and hospital settings. A study by Wang et al [56] of 100 prehospital arrests undergoing endotracheal intubation found that a fourth of CPR interruptions were due to placement of an ETT. Wang et al found that, on average, the first intubation attempt caused a 47-second pause in chest compressions. Because most patients required multiple attempts, the average patient lost a total of 110 seconds of chest compressions due to endotracheal intubation [56]. Prehospital intubation is responsible for significant pauses in compressions, yet it is not clear that these harmful effects are balanced by any survival benefit produced by early ETT placement. The OPALS study of Stiell et al [57] showed that trauma patients receiving intubation and other advanced life-saving skills did not have an improved outcome when compared with those receiving basic life support; furthermore, the most seriously injured patients fared worse with advanced techniques, including endotracheal intubation. The role of endotracheal intubation in the prehospital setting is widely debated, particularly early cardiac arrest resuscitation [58-60]. As the focus of CPR moves toward continued chest compressions, alternative airway management options among this subset of patients are being explored and should be considered in cardiac arrest management.

For instance, a study by Bobrow et al [21] explores passive oxygenation as an alternative to BVM ventilation in cardiac arrest patients. In this study, “passive oxygenation”—high-flow oxygen delivered via nonrebreather mask with an oral airway in place—was compared with traditional positive pressure ventilation with a BVM device in out-of-hospital cardiac arrest patients. Overall, neurologically intact survival was similar between these 2 groups. Yet, in the subset of patients with witnessed VF arrests, survival with passive oxygenation was 38% compared with 26% for those receiving active ventilation with a BVM device.

Cardiac arrest patients may fare less well with positive pressure ventilation simply because of the significant pauses in chest compressions caused by complex airway intervention. For example, a study by Steen et al [61] showed that blood oxygenation and coronary perfusion pressure were better for swine receiving passive oxygenation than for those receiving active ventilation via an ETT during CPR. Another study by Hayes et al [62] found that survival was similar for passive oxygenation and positive pressure ventilation via ETT in swine. In addition to causing harmful pauses in chest compressions, Aufderheide et al [63] suggest that positive pressure ventilation may directly harm cardiac arrest patients. In this study, increased intrathoracic pressure was found to cause a significant drop in coronary perfusion pressure and adversely impact outcomes [63]. These studies suggest that positive pressure ventilation may be fundamentally harmful for patients in cardiac arrest in addition to causing significant interruption in chest compressions that cannot be justified by any survival benefit over passive oxygenation.

2.6. Vascular access

When intravenous access is necessary during resuscitation, peripheral intravenous (PIV) access is the preferred method of gaining access. Intraosseous (IO) access is an acceptable alternative approach to PIV catheter placement in certain cases, particularly those involving difficult intravenous access. Because of the speed and high success rate associated with IO vascular access, it should be emphasized as an important part of adult cardiac arrest management. For instance, a study by Reades et al [64] comparing PIV, tibial IO, and humeral IO vascular access found that the success rate on first attempt with tibial IO access was superior to both humeral IO access and PIV access (91%, 51%, and 43%, respectively). In addition, the amount of time required to establish access was shortest in the tibial IO access arm (4.6 minutes for tibial IO access, 7.0 minutes for humeral IO access, and 5.8 minutes for PIV access) [63]. Another study comparing the time required to establish PIV and IO access found that IO access is 20 seconds faster than PIV access [65]. Although the difference in time required to establish IO and PIV access is relatively small, there is potential for this effect to be magnified in patients requiring multiple PIV access attempts. Considering the safety [66] and ease of use [67] of modern IO devices, there should be a very low threshold for providers to attempt IO access in cardiac arrest cases where there is difficulty establishing PIV access. Furthermore, the placement of a central venous catheter during active resuscitation is likely not indicated in most arrest scenarios. Such placement likely will detract from appropriate chest compressions if not cause further interruptions. If vascular access is felt necessary in the early phase of cardiac arrest management, then IO placement is strongly encouraged as long as its placement does not hinder the performance of high-quality, uninterrupted chest compressions.

3. Conclusion

Minimally interrupted chest compression in CPR is a potentially useful concept that is currently underused. To responsibly put this idea into practice may require differentiation of what is now cardiac arrest into more specific etiology-based entities: primary cardiac arrest, asphyxial arrest, and hypovolemic arrest. In many cases, it may be difficult to determine what is causing a patient's cardiac arrest, especially in a timely enough manner to not compromise the effectiveness of resuscitation. Despite this apparent difficulty, making this distinction is important because the studies reviewed here show that early and uninterrupted compressions in primary cardiac arrest patients have the potential to dramatically change outcomes. Uninterrupted chest compressions may not be as important to these other etiologies of cardiac arrest; instead, aggressive airway management and fluid resuscitation may have more of an important role. This appears to be especially relevant for pediatric patients, for whom primary cardiac arrest is relatively uncommon [68,69].

Of course, exceptions to the "airway- and vascular access–second" strategy are encountered in clinical medicine. First, it is important to note that the word "early" is applied here. The airway should be managed invasively once appropriate chest compressions have been initiated and sustained and defibrillation has occurred; management of the airway must not hinder appropriate chest compressions and other basic, yet key, interventions. Similarly, attempts at vascular access should not interrupt chest compressions. Second, in cardiac arrest scenarios in which a compromised airway, inadequate oxygenation and ventilation, hypovolemia, or other causative event is encountered, earlier management of these issues is encouraged. Such scenarios include, but are not limited to, cardiac arrest precipitated by hypoxia from pulmonary disease, hypercarbia precipitated by obstructive disease including obstructive sleep apnea and other hypoventilatory situations, and significant hypovolemia/hemorrhage preceding cardiac arrest.

Worldwide, most cardiac arrests each year are not caused by hypovolemic or asphyxial etiology but by a primary cardiac arrhythmia such as VF [70]. The studies reviewed in this article show that a resuscitation protocol with emphasis on uninterrupted chest compressions (such as CCR) has potential to improve outcomes for adult cardiac arrest patients. In addition, multiple major sources of chest compression interruption—pulse determination, cardiac rhythm interpretation, electric defibrillation, airway management, and vascular access—have been discussed along with potential solutions to minimize interruptions without significantly sacrificing the benefits of these interventions. Moving the focus toward continuous compression CPR—without interruption—has the potential to improve meaningful survival in cardiac arrest and thus save thousands of lives each year.

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